

CONSTRAINTS ON HELIUM ENHANCEMENT IN THE GLOBULAR CLUSTER M3 (NGC 5272): THE HORIZONTAL BRANCH TEST

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ApJ (Letters), in press

ABSTRACT

It has recently been suggested that the presence of multiple populations showing various amounts of helium enhancement is the rule, rather than the exception, among globular star clusters. An important prediction of this helium enhancement scenario is that the helium-enhanced blue horizontal branch (HB) stars should be brighter than the red HB stars which are not helium-enhanced. In this *Letter*, we test this prediction in the case of the Galactic globular cluster M3 (NGC 5272), for which the helium-enhancement scenario predicts helium enhancements of $\gtrsim 0.02$ in virtually all blue HB stars. Using high-precision Strömgren photometry and spectroscopic gravities for blue HB stars, we find that any helium enhancement among most of the cluster's blue HB stars is very likely less than 0.01, thus ruling out the much higher helium enhancements that have been proposed in the literature.

Subject headings: stars: abundances — Hertzsprung-Russell diagram — stars: evolution — stars: horizontal branch — (Galaxy:) globular clusters: general — (Galaxy:) globular clusters: individual (M3 = NGC 5272, M13 = NGC 6205)

1. INTRODUCTION

Globular star clusters (GC's) have traditionally been assumed to be excellent approximations to so-called "simple stellar populations," which are idealized systems in which all stars were formed at precisely the same time, from a chemically homogeneous cloud. However, recent observations, both photometric and spectroscopic, have cast serious doubts on this long-standing paradigm.

The presence of large abundance anomalies was first identified in the GC ω Centauri (NGC 5139). In this cluster, not only such light elements as C, N, O, F, Na, Mg, and Al, but also the Fe-peak, s-process, and r-process elements, are seen to vary by large amounts from one star to the next (e.g., Johnson et al. 2008, and the extensive list of references provided therein). Many of these abundance patterns seem to extend all the way down to the main sequence (e.g., Stanford et al. 2008). This strongly suggests that such abundance anomalies owe their origin to multiple star formation episodes within the cluster, each accompanied by a corresponding enrichment of the intrachuster medium by the ejecta of the massive and intermediate-mass stars which were formed in the prior stellar generations. While a large spread in Fe-peak abundances has only been detected in ω Cen, many of ω Cen's abundance anomalies have also been found in other clusters, albeit often at a (much) less dramatic level (e.g., Sneden et al. 2004; Johnson et al. 2005; Yong et al. 2009; see

also Gratton et al. 2004, for a recent review).

Analyses of the multiple main sequences found in the deep color-magnitude diagrams (CMD's) of ω Cen strongly suggest that the *helium abundance* Y in the cluster may also have changed dramatically from one star formation episode to the next (e.g., Norris 2004; D'Antona et al. 2005; Piotto et al. 2005). Recent evidence suggests that other clusters may also show sizeable Y variations. According to the deep CMD analysis of NGC 2808 by Piotto et al. (2007), multiple populations with different helium abundances are also present in this cluster. Strong arguments have also been raised in favor of helium enhancements among at least some of the stars in NGC 6388 and NGC 6441 (see, e.g., Catelan et al. 2006; Caloi & D'Antona 2007, and references therein). Interestingly, these four GC's figure among the most massive of all Galactic GC's.

Very recently, it has been suggested that multiple star formation episodes in GC's, accompanied by widely different amounts of helium enrichment, are in fact not the exception, but instead the rule (D'Antona & Caloi 2008). In the particular case of M3 (NGC 5272), such a claim had previously been made also by Caloi & D'Antona (2008), on the basis of an analysis of the period distribution of M3's RR Lyrae variables and the color extension of the HB blueward of the instability strip. Due to the recognized need to assume a very sharply peaked mass distribution to account for the sharply peaked shape of the RR Lyrae period distribution in M3 (Rood & Crocker 1989; Catelan 2004; Castellani et al. 2005), D'Antona & Caloi suggested that the mass distribution of HB stars is *always* sharply peaked, and that the color spread routinely observed in GC CMD's is instead due to internal variations in the helium abundance Y . It is important to emphasize that such a spread in Y is *not* required to explain the observed period distributions. Rather, the case for helium enhancement, at least in the case of M3-like clusters, rests almost entirely on the presence of color spreads among HB stars.

If confirmed, this scenario would not only have major implications for our understanding of how GC's form, but would

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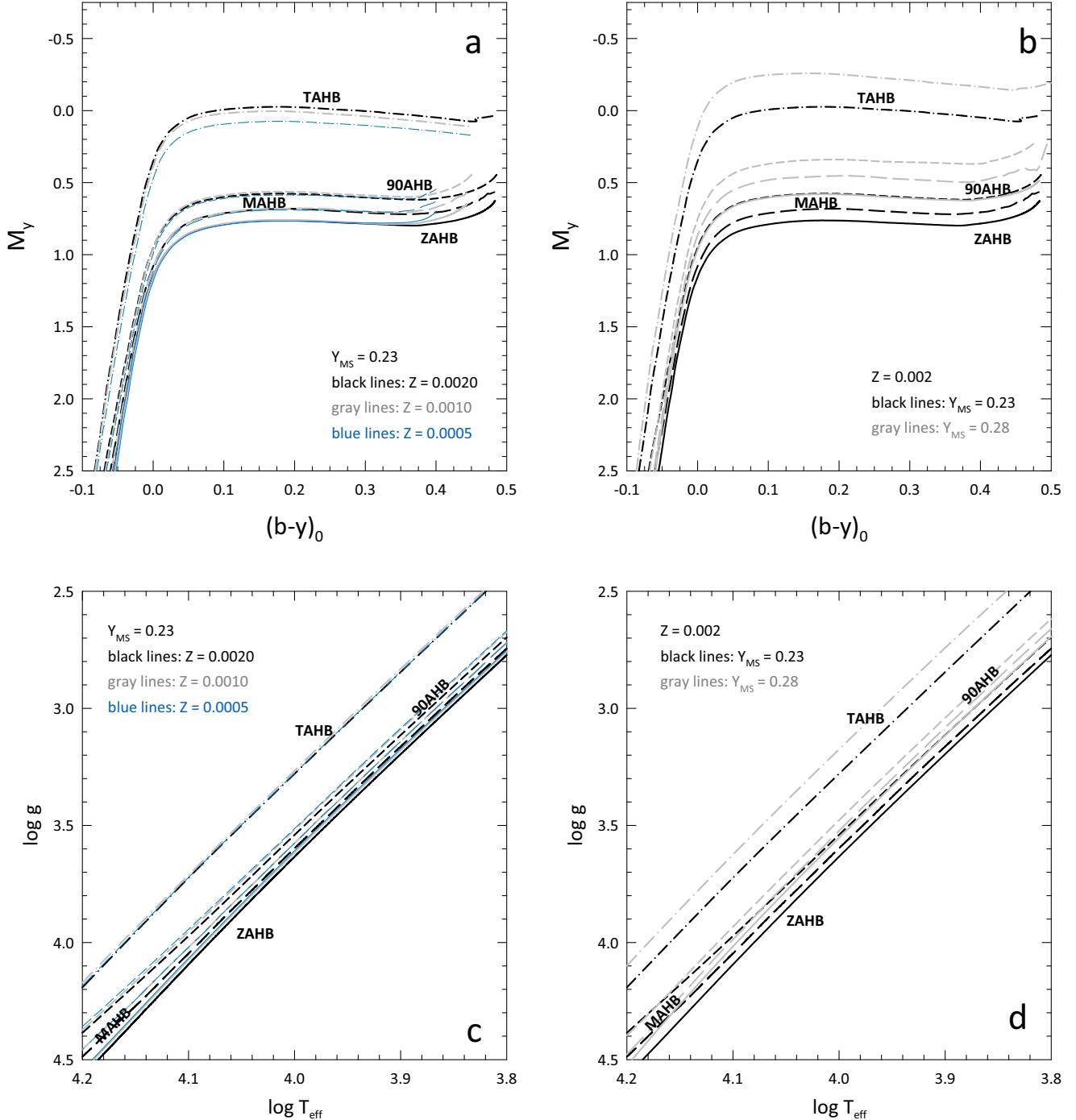


FIG. 1.— *Panel a:* comparison between fiducial HB loci (ZAHB, MAHB, 90AHB, TAHB; see definitions in §3) for three different metallicities (black lines: $Z = 0.002$; gray lines: $Z = 0.001$; blue lines: $Z = 0.0005$), in the M_y , $(b-y)_0$ diagram. To produce this plot, the $Z = 0.001$ loci were shifted in M_y by +0.075 mag, and the $Z = 0.0005$ loci by +0.140 mag. Note that with these shifts all three of the ZAHB's coincide, except at the extreme red end of the HB, where no unevolved stars are found in M3. *Panel b:* as in panel a, but for a fixed metallicity and two different helium abundances (black lines: $Y = 0.23$; gray lines: $Y = 0.28$), and without applying any shifts to the CMD positions. Panels *c* and *d*: as in *a* and *b*, but in the $\log g$, $\log T_{\text{eff}}$ plane, and without applying any shifts to the data.

also represent a major shift from the canonical paradigm, dominant since the late-1960's/early-1970's (Castellani et al. 1969; Iben & Rood 1970; Faulkner 1972; Rood 1973), which ascribes the color spread seen among HB stars to the stochastic nature of mass loss on the red giant branch (RGB). In the canonical scenario, blue HB stars lose significantly more mass as they climb up the RGB than do their red HB counterparts. In contrast, in the D'Antona & Caloi (2008) scenario blue HB stars, even at the “horizontal” level of the HB, owe their blue

colors to a higher initial Y . In the specific case of M3, the predicted He enhancement, even in the “horizontal” blue HB stars, should fall in the range between 0.02 and 0.025, according to Fig. 4 of Caloi & D'Antona (2008).

Fortunately, the Y enhancement scenario can be tested, using a variety of photometric and spectroscopic tools, especially for these moderately cool blue HB stars at the “horizontal” level. In particular, it is well known that HB stars with higher Y are brighter, at a given T_{eff} , due to their stronger

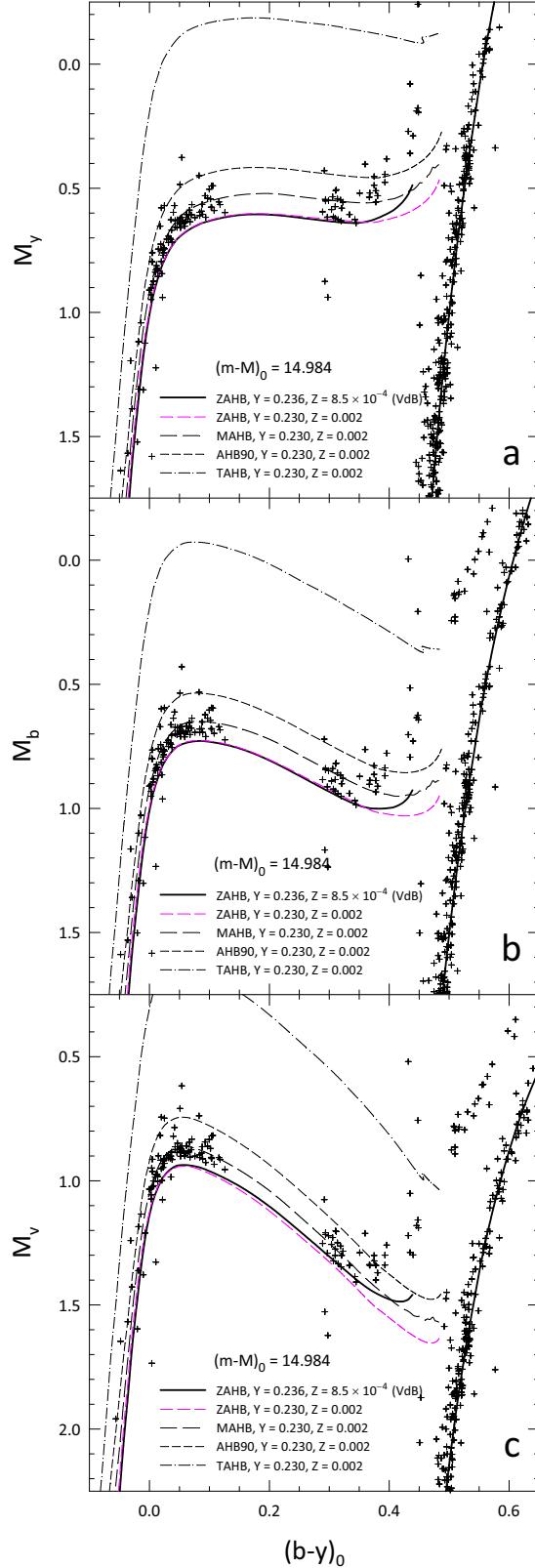


FIG. 2.—Comparison between fiducial HB sequences (see text) and the empirical data for M3, in the M_y , $(b-y)_0$ plane (panel a), M_b , $(b-y)_0$ plane (panel b), and M_v , $(b-y)_0$ plane (panel c). The empirical data were shifted vertically so as to produce a satisfactory match to the theoretical red ZAHB, as given by the VandenBerg et al. (2006) models for $[\text{Fe}/\text{H}] = -1.61$, $[\alpha/\text{Fe}] = +0.3$, and $Y = 0.236$, in the M_y , $(b-y)_0$ plane. The VandenBerg et al. RGB sequence is also displayed.

H-burning shells (e.g., Sweigart & Gross 1976). Therefore, in the D’Antona & Caloi (2008) scenario bluer HB stars should be brighter than their redder counterparts. While this may help account for the sloping natures of the HB’s in the moderately metal-rich GC’s NGC 6388 and NGC 6441 (e.g., Busso et al. 2007, and references therein), such a CMD test has never been carried out for most of the GC’s that, according to D’Antona & Caloi, present multiple He-enhanced populations.

The purpose of this *Letter* is accordingly to present a first test of the helium enhancement scenario, in the specific case of M3, by comparing high-precision photometry for the cluster in the Strömgren (1963) system, as well as spectroscopically derived gravities, with theoretical HB models computed for a variety of Y values.

2. OBSERVATIONAL DATA

The CMD data used in this paper were taken from Grundahl et al. (1998, 1999), to which the reader is referred for additional details regarding the calibration of our photometry. Briefly, our M3 photometry is based on a series of images obtained on the Nordic Optical Telescope, using the thinned AR-coated 2048×2048 pixel HiRAC CCD camera, with $0.11''$ pixel size, thus covering approximately $3.75'$ on a side. Two overlapping fields were observed, with one field centered on the cluster center to ensure a large sample of HB and RGB stars.

In addition to the CMD data, we also used the gravities and temperatures derived by Behr (2003), on the basis of observations using the HIRES cross-dispersed echelle spectrograph on the Keck I telescope.

3. THEORETICAL MODELS

In the present paper, we use the evolutionary tracks computed by Catelan et al. (1998) and Sweigart & Catelan (1998) for scaled-solar, heavy-element abundances Z of 0.0005, 0.001, and 0.002. Evolutionary tracks for a He abundance $Y = 0.23$ by mass were computed for each of these Z values. Additional He-enhanced tracks for $Y = 0.28$, 0.33 were also computed for $Z = 0.002$.⁷ The theoretical models were transformed to the Strömgren (1963) $uvby$ system by using the color transformations and bolometric correction tables provided by Clem et al. (2004). The same procedures were also adopted in the recent work by Catelan & Cortés (2008) and Cortés & Catelan (2008), where the period-color and period-luminosity relations of RR Lyrae stars in the Strömgren system were presented. In addition, we also use a set of models computed by VandenBerg et al. (2006), for a chemical composition $[\text{Fe}/\text{H}] = -1.614$, $[\alpha/\text{Fe}] = +0.3$ (which translates, according to those authors, to a $Z = 8.45 \times 10^{-4}$), and $Y = 0.236$.

M3 has a metallicity of $[\text{Fe}/\text{H}] = -1.57$ in the Zinn & West (1984) scale, and $[\text{Fe}/\text{H}] = -1.34$ in the Carretta & Gratton (1997) scale. Taking into account an enhancement of the α -capture elements by $[\alpha/\text{Fe}] = +0.27$ (Carney 1996), and using the relation between Z , $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$ from Salaris et al. (1993), we find an overall metallicity of $Z = 8.3 \times 10^{-3}$ and $Z = 1.4 \times 10^{-3}$, respectively, on these two metallicity scales. Therefore, our models comfortably bracket the range of possible metallicity values for the cluster.

⁷ Note that these helium abundances refer to the initial main sequence values, and thus do not include the small increase that occurs during the dredge-up phase on the RGB.

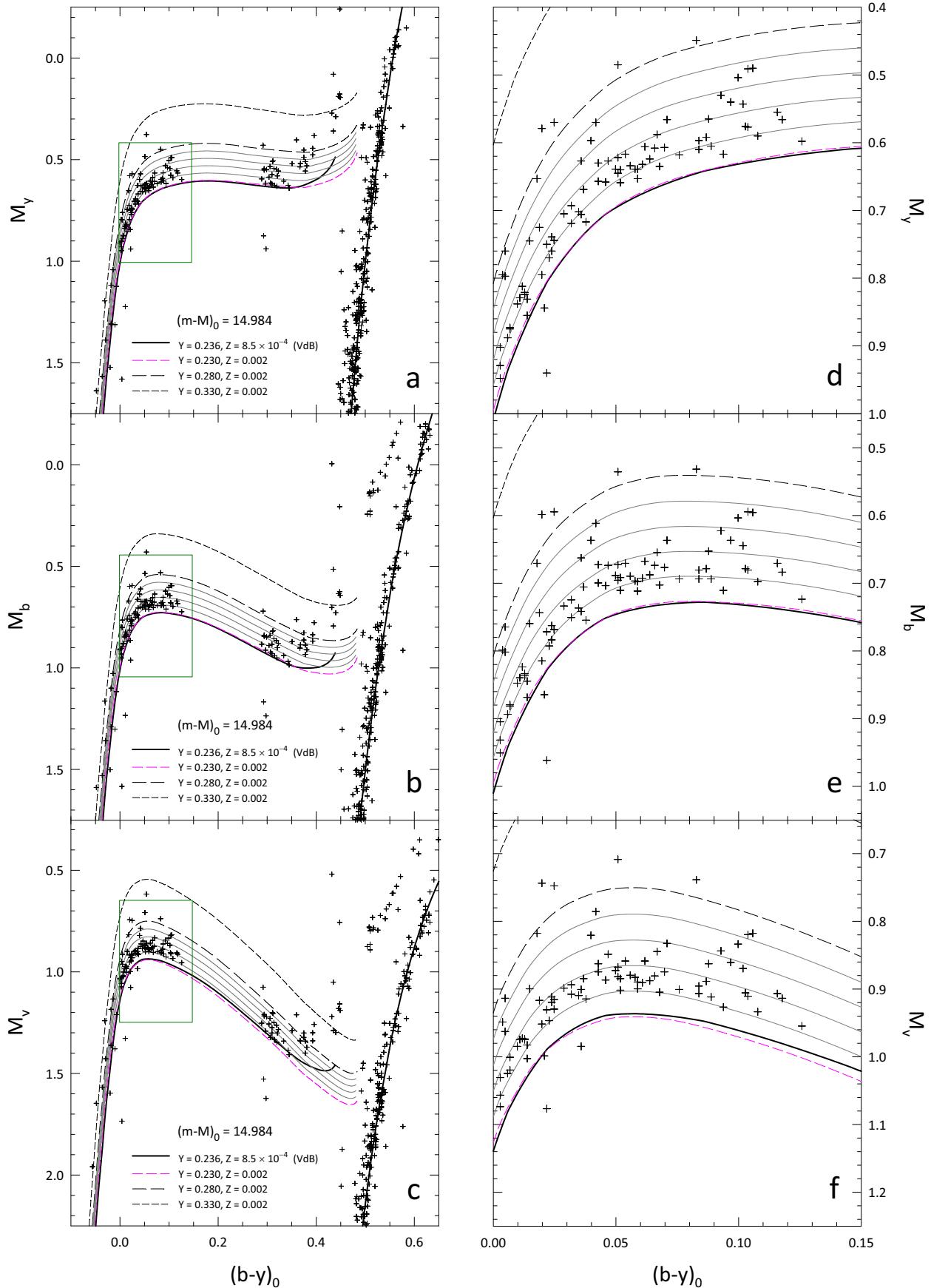


FIG. 3.— As in Figure 2, but plotting only the ZAHB's, for the several different Y values as indicated. The *thin solid lines* indicate interpolated ZAHB loci for Y values between 0.23 and 0.28, in intervals of 0.01. Panels *d* through *f* present expanded views of the rectangular box around the blue HB “knee” in panels *a* through *c*, respectively.

Since we are primarily interested in constraining the *change* in Y between the red and blue HB, the exact choice of Z value is basically irrelevant for our purposes. This is shown in Figure 1a, where our models for $Z = 0.0005$, $Z = 0.001$, and $Z = 0.002$ are compared in the M_y , $(b-y)_0$ diagram. To produce this plot, we first registered the low-metallicity zero-age HB (ZAHB) sequences to the $Z = 0.002$ ZAHB by shifting the $Z = 0.0005$ ZAHB by $+0.140$ mag and the $Z = 0.001$ ZAHB by $+0.075$ mag in M_y . We then applied the same shifts to the evolved HB sequences for each Z value, and derived several fiducial loci representing evolved HB stars, as follows: i) MAHB, standing for the *middle-age HB*, or HB ridgeline, which gives the average position occupied by all HB stars, assuming a uniform mass distribution along the entire ZAHB; ii) 90AHB, or *90%-age HB*, which is approximately the locus below which one should find $\approx 90\%$ of all HB stars;⁸ iii) TAHB, or *terminal-age HB*, which is simply the He exhaustion locus.

This registration procedure clearly leads to an excellent match over the entire range of ZAHB colors and HB luminosities, except (as expected) at the extreme red end of the HB and close to the TAHB. Since M3 lacks unevolved HB stars at colors redder than about $(b-y)_0 \simeq 0.34$, and since the TAHB lies very far away from where most HB stars are found (see Fig. 2), these differences are of no concern for our purposes. Similar results follow when using M_b and M_v , but not M_u , which we have found to be affected by strong metallicity effects. Since the v - and (especially) the u -band bolometric corrections from Clem et al. (2004) may be quite uncertain (D. A. Vandenberg, priv. comm.), we have decided not to include our u -band photometry in this *Letter* (but see Catelan 2009b). We will, however, include our v -band data, but caution that the comparison of these data with the models is less reliable than for the y or b data.

While the metallicity effects are clearly mild, both the ZAHB and the evolved HB loci depend strongly on Y , as can be easily inferred from Figure 1b. This shows that a *differential* comparison between the luminosities of red and blue HB stars, around the metallicity of M3, should provide a strong indicator of any possible helium enhancement, with only a very mild dependence on metallicity.

Panels *c* and *d* in Figure 1 reveal the effects of metallicity and Y , respectively, on the $\log g - \log T_{\text{eff}}$ plane. This again shows that metallicity plays but a minor role in defining the position of a star on this plane, compared with Y .

4. RESULTS

We compare the model predictions for fixed (low) Y with the empirical CMD data in Figure 2. To produce these plots, we have first corrected the empirical data for reddening using a $E(B-V) = 0.01$, taken from Harris (1996), and the extinction coefficients for the Strömgren system summarized in Catelan & Cortés (2008). We then shifted the data vertically, as required to match the theoretical red ZAHB computed by Vandenberg et al. (2006) to the lower envelope of the observed distribution in the M_y , $(b-y)_0$ plane. Note that these Vandenberg et al. evolutionary tracks also provide an excellent fit to the RGB of the cluster. This results in a distance modulus of $(m-M)_0 = 14.984$ for M3. We then applied

⁸ In like vein, one may define the “50%-age HB” locus, or 50AHB, as the locus occupied by HB stars of different masses which have completed 50% of their HB evolution. Note, however, that this is not exactly coincident with the MAHB; since the distribution of HB luminosities is not Gaussian, the MAHB is in fact slightly more luminous than the corresponding 50AHB.

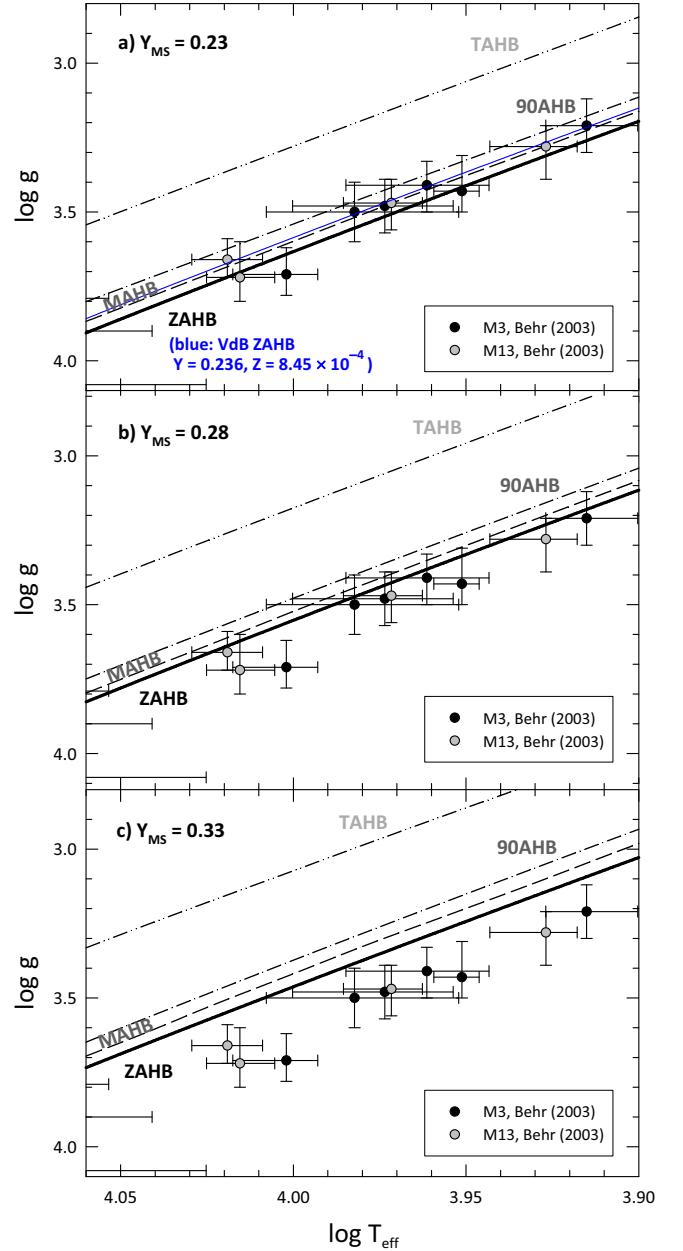


FIG. 4.— Comparison between predicted and observed loci in the $\log g$ – $\log T_{\text{eff}}$ plane, for a metallicity $Z = 0.002$ and three different helium abundance values: 0.23 (panel *a*), 0.28 (panel *b*), and 0.33 (panel *c*). Empirical data are provided for M3 (black circles) and M13 (gray circles), from Behr (2003). The blue line in panel *a* shows the ZAHB locus of Vandenberg et al. (2006) models for a $Y = 0.236$, $[\text{Fe}/\text{H}] = -1.61$, $[\alpha/\text{Fe}] = +0.3$.

a shift of $\Delta\text{mag} = -0.16$ to our $Z = 0.002$ models, in order that they would match the Vandenberg et al. ones. As can be seen, such a procedure leads to an excellent morphological match between the Vandenberg et al. ZAHB for $Z = 8.45 \times 10^{-4}$ and our own for $Z = 0.002$, especially in the M_y , $(b-y)_0$ and M_b , $(b-y)_0$ planes, except again at the very end of the red HB distribution, where no unevolved HB stars are found in M3.

Except perhaps for a small deviation of the lower envelope of the blue HB stars in the immediate vicinity of the “knee” from the theoretical (single- Y) ZAHB, this figure shows a remarkable overall agreement between the model predictions and the observations, without an immediately obvious need to invoke an increase in Y for the blue HB stars. In addi-

tion, all the other HB fiducials for a fixed Y , including the MAHB, 90AHB, and TAHB, appear to describe the empirical data fairly well, without significant evidence for an excessive number of overluminous blue HB stars, as would be expected in the helium-enhancement scenario (see Fig. 1b). To be sure, the evolutionary lifetimes along the canonical tracks do not provide a perfect match to the CMD distribution (Valcarce & Catelan 2008); however, it appears extremely unlikely that any such disagreements may somehow be due to internal variations in Y , since they seem to affect blue *and red* HB stars alike, as also noted by Valcarce & Catelan.

In Figure 3 we compare our CMD data to ZAHB sequences for different Y values in order to obtain a more quantitative limit on any increase in Y between the red and blue HB populations. These ZAHB sequences are all for a fixed $Z = 0.002$ and have been shifted by $\Delta\text{mag} = -0.16$ to match the VandenBerg et al. (2006) ZAHB for $Z = 8.45 \times 10^{-4}$, as noted previously.

Clearly, an enhancement in Y by more than 0.01 in the blue HB stars would hardly be compatible with the data. In particular, we find many more stars below the blue ZAHB for $Y = 0.24$ than below the red ZAHB for $Y = 0.23$, again with the possible exception of the (more uncertain) $M_v, (b-y)_0$ plane. This strongly suggests that the level of He enhancement is most likely less than 0.01 among the cool blue HB stars in M3.

Recall, from Figure 4 in Caloi & D'Antona (2008) and Table 1 in D'Antona & Caloi (2008), that the bulk of the blue HB stars in M3 are predicted, in the helium-enhancement scenario, to be enriched in the range between 0.02 to 0.025. Such a level of helium enhancement is clearly ruled out by our data. Note also that, in the helium enhancement scenario, one should expect to see an increase in Y towards bluer colors, but this is not supported by our data.

Finally, Figure 4 compares the empirical and predicted positions of blue HB stars in M3 in the $\log g, \log T_{\text{eff}}$ plane, for three different helium abundances, ranging from 0.23 (panel *a*) to 0.33 (panel *c*). To produce this plot, we restrict our-

selves to temperatures cooler than 11,500 K, to avoid the well-known complications due to radiative levitation for hotter HB stars (Grundahl et al. 1999; Michaud et al. 2008). Our CMD's indicate that less than 5% of all of the HB stars in M3 are hotter than this limit, which corresponds to a color $(b-y)_0 \approx -0.025$.

Similarly to what was found in our CMD analysis, the empirical gravities also seem entirely consistent with a uniform value of Y among the blue HB stars in M3. In addition, there is no indication of an increase in Y beyond the canonical value, a conclusion which becomes even stronger when the data are compared with the α -enhanced ZAHB by VandenBerg et al. (2006) for a $Y = 0.236$, $Z = 8.45 \times 10^{-4}$. Interestingly, the available data also suggest that at least the redder blue HB stars in M3 (NGC 6205) have a similar helium abundance as in M3. The sample size remains relatively small though, and therefore data for more stars in both clusters would certainly prove of interest to derive more conclusive results.

5. CONCLUSIONS

In this *Letter*, we have shown that high-precision, well-populated empirical CMD's, along with spectroscopic gravities, can be used to pose strong constraints on the presence of helium-enriched populations in GC's. Our results strongly suggest that any populations that may have formed after a main initial burst in M3 likely preserved closely the same helium content as in the cluster's primordial gas, with a level of helium enhancement most likely not higher than 0.01. In future papers, we plan to apply similar tests to several other GC's.

We thank an anonymous referee for some helpful comments, and D. A. VandenBerg for some enlightening discussions. Support for M.C. is provided by Proyecto Basal PFB-06/2007, by FONDAP Centro de Astrofísica 15010003, by Proyecto FONDECYT Regular #1071002, and by a John Simon Guggenheim Memorial Foundation Fellowship.

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